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Applications of Lasers

C. MARTIN STICKLEY

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Abstract

Fundamentally this article is a survey of applications of lasers. The applications are divided into six major areas: precision measurements, communications, biological and medical, other scientific areas, metalworking, and miscellaneous. A table of the basic characteristics of the major types of lasers is provided so that the user can be made aware of the limitations and capabilities of lasers. Good examples of applications in each of these areas are described in some detail to illustrate which major properties of laser radiation are useful in that particular area. Most of the discussion pertains to present-day applications but in some instances what appear to be good future applications are also described. Seventy-two references to the technical literature that relate to applications are provided.

Contents

Applications of Lasers

1. INTRODUCTION

With the laser, man can now for the first time generate and control coherent light by making use of electronic transitions in atoms. Many knowledgeable people have predicted a glorious future for lasers, but others have been considerably more skeptical. Four years have elapsed since the first working laser was announced, and fewer than ten different applications today are not connected with research and development. The widest application so far has been in scientific instrumentation such as light sources for interferometers and high-energy sources for investigating interactions between photons and matter. Whether this will remain as the most prolific application is difficult to say for it could be that the best application may not yet have been thought of.

The primary properties of the laser—directionality, monochromaticity, intensity, and coherency—are reviewed in Sec. 2 of this paper. Sections 3 to 8 deal with actual and proposed applications. References pertinent to the area covered appear at the end of each section.

The applications that depend on a particular property of laser radiation are listed in Table 1. This is arbitrary in many cases.

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TABLE 1. Applications and primary laser properties

	Coherence	Narrow Optical Frequency	Narrow Beam Divergence	High Intensity
Mechanical Measurement	x			
Standard of Length		x		
Seismograph		x		
Rotation-Rate Sensor	x			
Tracking Systems			x	
Communications	x			
Power Transmission			x	
Raman Spectroscopy		x		
Relativity Experiments		x		
Plasma Diagnostics				x
Microscopic Spectroscopy				x
Phase Photography	x			
Defense				x
Metalworking				x

2. PRIMARY PROPERTIES OF LASER RADIATION

2.1 Frequency Stability, Intensity, and Directionality

The four major properties of laser radiation are high intensity, narrow frequency width, directionality, and coherence. These are summarized in Table 2. The minimum frequency widths given for the gas[1] and optically pumped solid lasers[2] are short-term measurements based on single-frequency operation. For the He-Ne gas laser the stability time is on the order of tens of milliseconds and for the ruby laser it is 2μsec. The line width of the ruby laser is determined by both the Fourier spectral components of the spike and the thermal drift during the spike. A detailed measurement of this type has not been made for the injection laser, but calculations and probably spectrometer-limited measurements[3] indicate it is in the 10 to 50 Mcps range. As the pump level increases, more resonant modes of the laser cavity are excited, each of which has the widths indicated under Minimum Frequency Width, but the total spectral range of these different modes is that indicated under Frequency Width at High Power.

The peak power indicated for gas lasers was obtained by pulsing an argon gas column with a capacitor discharge;[4] the duration of these pulses was about 20 nsec. At lower power levels, repetition rates can be on the order of 1000 pps. For ruby, 500 Mw was obtained[5] by using a Q-switched system (rapid increase in positive feedback in a cavity) followed by a stage of amplification, the duration of this pulse was about 7 nsec. Energies of 1500 j have been listed in the advertising literature. These are difficult to confirm owing to measurement problems and repeatability of experiments.

The repetition rate given for the pulsed gas laser does not represent an upper

TABLE 2 Output characteristics of lasers

	Gas		Optically Pumped Solid		Injection	
	continuous wave	pulsed	continuous wave	pulsed	continuous wave	pulsed
Min. Freq Width	8 parts/10^4	-	3 Mcps (spacing type)	[illegible] Mcps	10 to 50 Mcps	
Freq Resettability	0.5 Mcps	-	-			
Freq Width at High Power	2.0 Gcps	-	-	40[illegible] cps (0.5 Å) (ruby); [illegible]Å (glass)	20 Å	
Peak Power	-	100 w	-	[illegible]$\times 10^4$ w	-	1000 w (77°K) 14 w (25°C)
Max. Energy	-		-	1500 j (ruby) 2000 j (glass)	-	
Repetition Rate	-	1000 pps	-	60 pps	-	1000 pps
Max. cw Power	[illegible] w	-	[illegible] w	-	1.5 w (77°K) 2[illegible] w (25°C)	-
Beam Divergence	2×10^{-4} rad	-	-	10^{-3} rad	1°×15°	
Wavelength Range	0.3164 to 133μ	0.27 to 1.2μ	-	0.31[illegible] to 2.[illegible]μ	0.4[illegible] to 5.2μ	-
Tunability	-	-	-	[illegible]Å (glass)	[illegible]Å	
Efficiency	0.2%	-	-	1% (ruby) [illegible]% (glass)	[illegible]%	-
Relative Coherence	excellent	-		good	fair	-

limit but only the prf of the available power source (capacitor bank or magnetron). The optically and electron-injection pumped lasers are probably limiting this rate because of heating considerations.

The beam divergence listed for a gas laser is for one with plane parallel mirrors. Perhaps a more typical figure is 10^{-3} rad, which corresponds to the approximate beam divergence from a confocal resonator 1m long. The ease of mirror alignment makes this a much more popular type of gas laser. The figure of 10^{-3} rad for ruby is for a good ruby rod operated in a Q-switched system.[6] It must be emphasized that this is the half-power point, and for a Q-switched ruby laser there is still an appreciable amount of power in the beam at angles greater than 10^{-3} rad. Without beam attenuation, the angular spot size appears to be 10^{-2} rad. The beam divergence for semiconductor lasers is typically 1° by 15°, which is in rough agreement with diffraction theory ($\theta \approx \lambda/d$) for an aperture $d \approx 10\mu$. This is the approximate width of a p-n junction in a semiconductor laser. It is worthwhile noting that beam divergences are to a large extent controllable by using the technique shown in Figure 2.1. Assuming that the divergence of the beam entering from the left is limited by diffraction from an aperture equal to the diameter d_1 of the first lens, the beam emerging from the system in Figure 2.1 will have a divergence angle of λ/d_2 if the focal points of the two lenses coincide. Similarly, the beam can be spread further if it enters the large lens and emerges from the small lens.

Gas lasers can be built to cover a wavelength range[7,8] extending from 133μ (0.133 mm) to 0.27μ, which is a frequency range of over 500/1. Pulsed noble-gas lasers filled with a mixture of noble gases now provide for selection of the approximate wavelength desired by rotation of a prism inside the laser cavity.

Efficiencies are still low when computed in terms of electrical input to optical output. Gas lasers should become more efficient as a result of the triode structure[9] recently developed; the efficiencies of injection lasers should also improve (up to, say, 50 percent) from present measured values[10] of 15 percent.

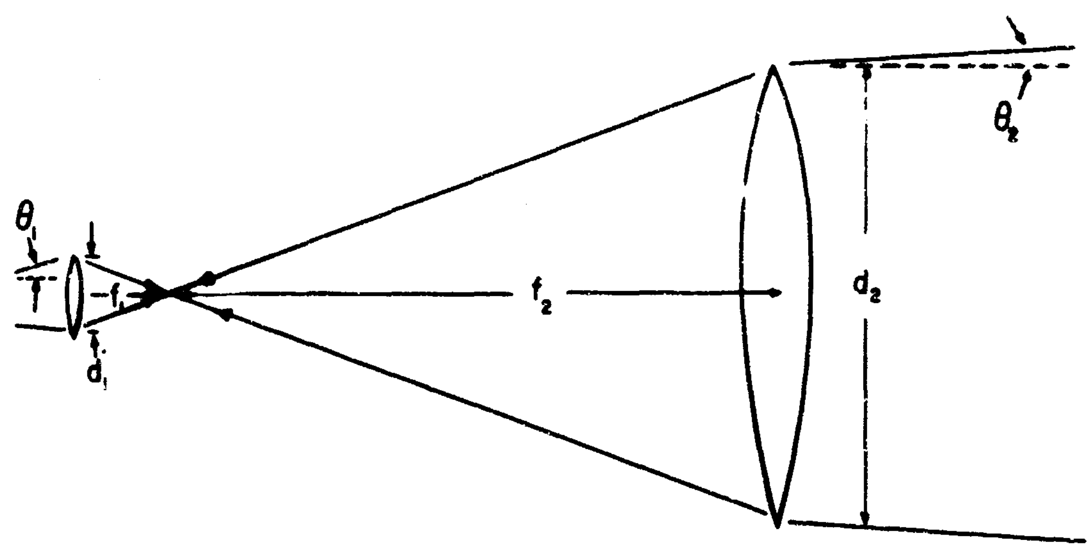

Figure 2.1. Optical System for Changing Beam Divergences

2.2 Spatial and Temporal Coherence

Coherence in the three types of lasers is compared only qualitatively in Table 2 because no quantitative measurements (in the sense of Born and Wolf's[11] definition) have to the writer's knowledge been made. A system for quantitative measurements was, however, recently proposed.[12] The meaning of coherence from Born and Wolf's definition is difficult to grasp, so we will discuss the more classical interpretation of it in terms of spatial and temporal coherence.

Spatial coherence of a wave can be illustrated by Young's double-slit interference experiment shown schematically in Figure 2.2. The wavefront spreads by diffraction from the two slits and interferes on the screen. In particular, at point P the <u>difference</u> in phase between the two waves originating from the slits is given by

$$\theta = \frac{2\pi d}{\lambda} \sin\phi \quad .$$

(This assumes the time delay between the two rays arriving at P is much less than

the temporal coherence time.) When θ is an even multiple of π, constructive interference occurs; when it is odd, destructive interference occurs. When the phase difference between the equal-amplitude waves at the two slits is the same over the duration of the measurement, there is a constant interference at P and the wavefront is said to possess spatial coherence. If the phase difference shifts appreciably during measurement, the position of the maximum in the neighborhood of P wanders and shows as a smear; this is what one observes with incoherent light. Thus, when the wavefront has a given constant amplitude, spatial coherence depends on a definite phase correlation between two points. When the wavefront is equiphased, spatial coherence depends on the condition that the amplitude at the two points is the same function of time.

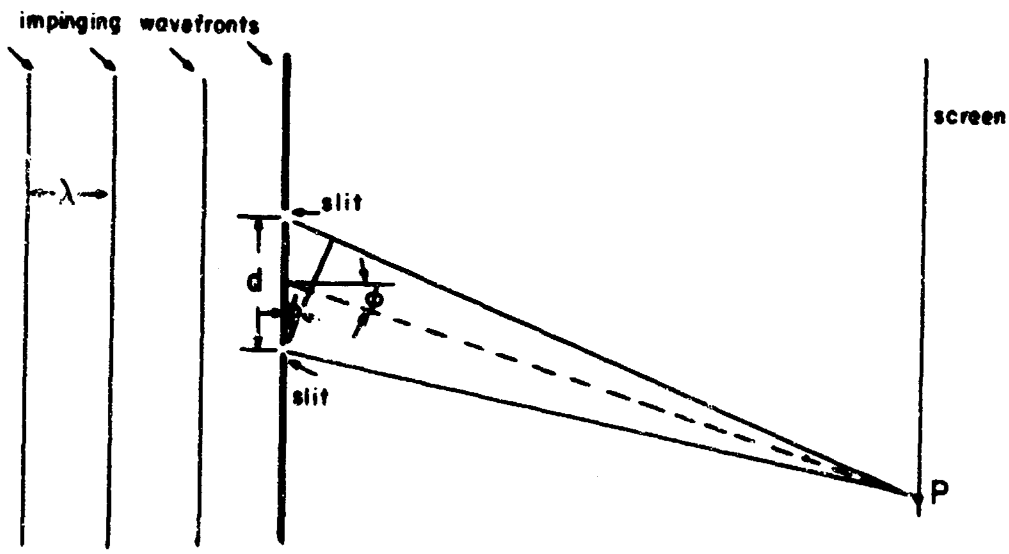

Figure 2.2. Experimental Setup for Measuring Spatial Coherence

The temporal coherence of a wave train that is known to be spatially coherent can be examined as in the following experiment.[13] As shown in Figure 2.3, half of the wavefront enters the upper slit and traverses the path to P; the other half of the wavefront is intercepted by mirror 1, directed to a movable prism that reflects it to mirror 2, and then reflected toward the lower slit where it interferes at P as in Figure 2.2. If $L = 0$, perfect stable fringes are seen on the screen since the wavefronts are spatially coherent. As L increases from zero, the wavefront is delayed by $2L/c$ (c is the velocity of light) and the interference at P can be studied as a function of the delay. If no fringes are seen on the screen when $L > 0$, then the wave has no temporal coherence. If the fringes become invisible for $t_o > 2L_o/c$, then t_o is the temporal coherence time. It can be related to the spectral width Δf of the radiation by

$$t_o \, \Delta f \approx 1 \, .$$

In summary, coherence implies a constant phase difference between two points on a series of equal-amplitude wavefronts, and a correlation in time between the same points on different wavefronts. For a high-quality stable gas laser, estimates have been made[1] that L_o could be as large as 10,000 miles. In measurements of L_o for ruby lasers[13] it was found that $L_o \approx 15m$, giving a t_o of 10^{-7} sec. This is in reasonable agreement with the spike duration in ruby lasers. Somewhat different measurements on injection lasers indicate that their coherence is not as good as that of ruby but that it is of course still far superior to that of normal light.

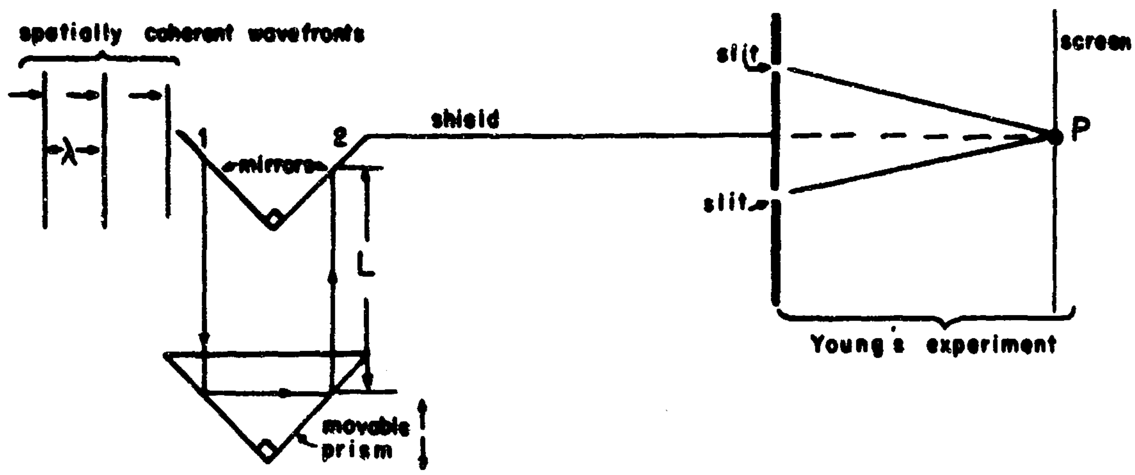

Figure 2.3. Experimental Setup for Observing Temporal Coherence

In conclusion, the radiation from optical masers is not at all like the radiation from previously known optical sources, as can be seen from the factors that have been discussed in this section. Its properties are more analogous to those of a parabolic antenna powered by an electronic transmitter. Thus, a better overall viewpoint is that the laser represents an extension of electronic technology by four orders of magnitude in frequency.

2.3 References

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3. APPLICATIONS IN PRECISION MEASUREMENTS

The use of lasers for precision measurements depends on the coherence of the laser beam rather than on its intensity. Because of their superior coherence, narrow frequency, and ability to operate continuously without having to be cooled, gas lasers will undoubtedly be preferred to solid lasers.

3.1 Mechanical Measurements

The standard type of interferometer used for measuring the quality of optical components (surface flatness, parallelism of mirrors, and index of refraction variations in glass) and for measuring distances in terms of the wavelength of light is the Michelson interferometer.[1] Referring to the illustration in Figure 3.1, if the difference d in length of the two arms L_1 and L_2 is an integral number of half wavelengths, or if the difference in total path length $2d$ is an integral number of full wavelengths, then the two beams will constructively interfere. The condition for seeing a bright fringe is therefore

$$2d = k\lambda \ ,$$

where λ is the wavelength of the light being used and k is an integer.

The cadmium red line is a conventional light source that can be used with this instrument but because its coherent length L_o is short, no fringes can be seen if d is made greater than 25 cm. If a gas laser is used, however, its excellent temporal coherence allows the two mirrors to be separated by 600 ft or more, resulting in a versatile instrument for measuring small differences over long path lengths. As an example, take the construction of the surface of a microwave antenna that is to be 100 ft or so in diameter. Good performance of the antenna depends on surface smoothness, which has heretofore been difficult to measure. Now, a beam could be reflected from the surface and brought back to interfere with itself (as in the Michelson interferometer), the number of fringes counted, and, as the beam swept around, the precision of the antenna cataloged. The laser interferometer could also be used for continuous, accurate measurement in machining, say, a large turbine shaft of a motor generator. Such a measurement is difficult with standard tools but

with a laser it could easily be done to within $\lambda/20$ or 3×10^{-6} cm by monitoring either a reflection from the shaft surface or a mirror mounted on the drive mechanism of the cutting tool. The depth of cut or variations in smoothness could easily be determined by means of an electronic counter and a photomultiplier.

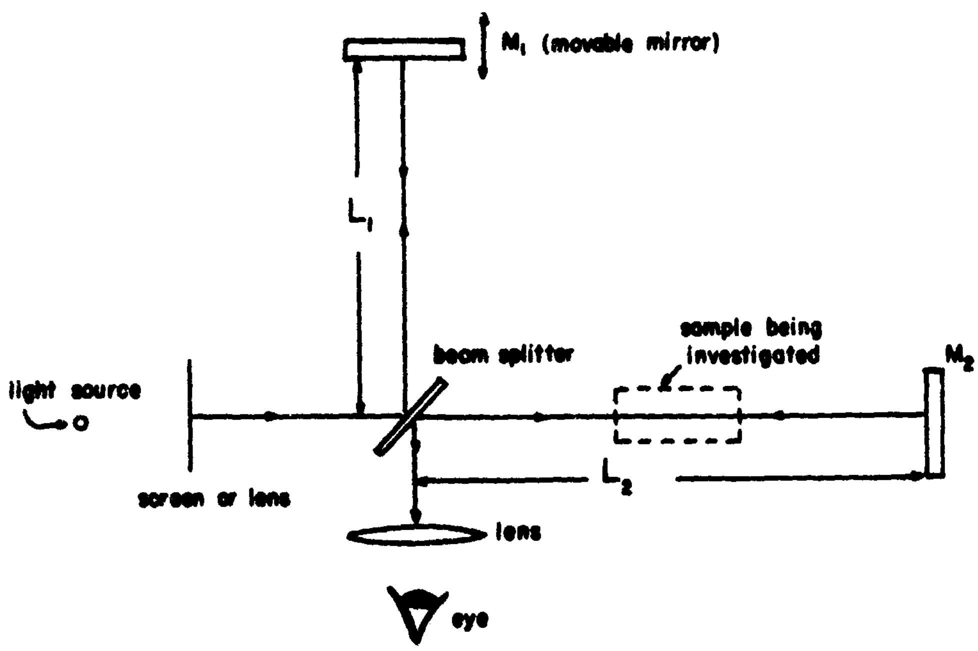

Figure 3.1. Michelson Interferometer

3.2 Standard of Length

Experiments by Jaseja, Javan, and Townes[2] indicate that a highly stabilized helium-neon gas laser can detect changes in length as small as eight parts in 10^{14}, equivalent to less than one wavelength of light in 10,000 miles. To detect such changes, the surface whose position is to be monitored must be used as one of the mirrors of the laser. The output of this laser is then mixed with that of a standard laser and the beat frequency Δf detected. The relation is

$$\frac{\Delta f}{f} = \frac{-\Delta L}{L} \;.$$

In practical application this method of length measurement is too sensitive. Such small changes in length are not normally required to be known, and their meaning in a path length of, say, 50 cm, would be difficult to define since ΔL would be on the order of a nuclear diameter (10^{-13} cm).

It is quite certain that the laser will become a standard of length. Jaseja et al.[2] demonstrated that they could reset one of their gas lasers to within 500 kcps, which is equivalent to resetability to within one part in 10^9. This is already superior to the present standard of length, and their technique for resetting the laser will probably improve further.

3.3 Seismographic Instrumentation

If one of the mirrors of the gas laser is attached to a large suspended mass[3] as shown in Figure 3.2, the instrument can be used as a detector of earthquakes or underground nuclear blasts since its sensitivity is estimated to be 10 times better than that of present seismometers. It is capable of covering a wide dynamic range (10^7) and a period range of seismic events from 0.1 sec to 40,000 sec or longer.

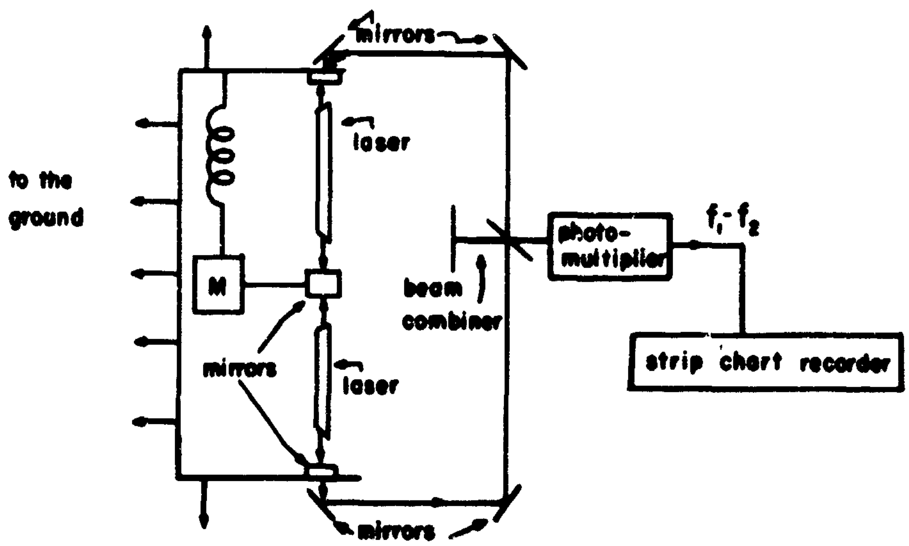

Figure 3.2. Seismographic Instrumentation

The instrument works as follows. When a disturbance in the earth occurs, the mass M moves and differentially shifts the frequency of the two gas lasers. The output beams are then mixed in a photomultiplier (a square-law device) and recorded. The beat frequency is directly related to the severity of the disturbance. The use of two lasers in this manner eliminates the requirement for having a separate absolute frequency standard.

3.4 Measurement of Rotation Rates

Another device that features gas lasers has recently been developed. It can provide extremely accurate measurements over a wide range of angular rotation rates, detect rotation rates as low as 5° per hour, and has no upper limit. Since its potential seems greater for use as a navigational aid, its discussion is postponed to Sec. 4.9.

3.5 References

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4. APPLICATIONS IN COMMUNICATIONS

This section is devoted to a discussion of the applicability of lasers to any type of system that comes under the broad heading of communications. Several existing applications in this area are considered in detail.

4.1 Applicability of Lasers to Communications

It is well known in the field of communication theory that the information capacity C of a signal of average power S in the presence of additive white noise power N in a channel of bandwidth B is given by

$$C = B \log (1 + S/N) \ .$$

This expression illustrates one reason there is a great interest in lasers for communication purposes: channel capacity is directly proportional to bandwidth—and the bandwidth for a laser communication system could be as large as, say, 40,000 Mcps. This is equal to 0.01 percent of the carrier frequency of 4×10^{14} cps. A bandwidth of this size would permit 10 million simultaneous telephone conversations or 8000 simultaneous TV programs. It is doubtful that there is a large need for many systems of this type, but the figures do indicate the attractiveness of the idea.

A system for modulating light with a bandwidth of 10 Gcps has been reported.[1] It seems likely that an upper limit might be 20 to 30 Gcps, based on the fact that all modulators will use microwave components and frequency ranges for given components are not much larger than this. It is interesting to note that we now have a situation in which the problem facing communications researchers is not how to conserve bandwidth, but how to make use of all the bandwidth available. This problem of how to build an extremely wide-band modulator to utilize the large bandwidths of optical channels is a real one, and will certainly be the limiting factor in the realization of an efficient optical communication system.

There are optical communication systems that use incoherent light but the use of coherent light greatly improves the detection sensitivity if the signal is weak or the receiver is being operated in daylight. In a conventional optical receiver, the signal alone is fed into the detector, and noncoherent detection performed. In a coherent optical receiver, the signal is mixed at the detector with a coherent optical local oscillator reference, and coherent detection performed. The gain in sensitivity obtained with coherent detection as opposed to noncoherent detection can be shown[1] to be

$$G = P_{ni}/P_{si}$$

for $P_{si}/P_{ni} < 1$, where P_{si} and P_{ni} are the optical input signal and noise powers, respectively. If the signal-to-noise ratio is somewhat greater than unity, then noncoherent detection is sufficient.

A ranging system needs a pulse with a sharp well-defined leading edge so that an accurate measurement can be made of the elapsed time. Fast Q-switched laser systems followed by a stage of amplification can produce optical pulses with a rise time on the order of a nanosecond. Assuming an electronic detection system in the receiver that could keep pace with this fast a pulse, there could be a range resolution of 6 in. This optical radar could easily be used on the ground since the beam diameter is very small and the divergence angle low. These factors cut down on spurious reflections from other objects and consequently reduce the background noise level.

Another distinct advantage in using light as the carrier in a communication system is the small size of the equipments involved. To obtain the same angular resolution as a radar operating with a wavelength of 1 cm, the antenna for the laser system can be 10^{-4} times as small for a laser wavelength of 1μ. With transmitting and receiving apertures of this size, relatively small mounts that are highly accurate and stable can be designed.

4.2 Ruby-Laser Tracking System

A number of ranging systems have been built by various laser research and development groups in the country. Since this is one of the primary systems uses of lasers, we will discuss one pulsed ruby-laser ranging system and also a more refined missile-tracking system using a gas laser.

The portable ranging system shown schematically in Figure 4.1 was developed by personnel[2] at the United States Army Electronics Research and Development Laboratory, Fort Monmouth, N.J. A Q-switched ruby laser serves as the transmitter for the system. A 90° ruby crystal 3 in. long and 1/4 in. in diameter generates a single pulse of 1.0 to 2.5 Mw. The Q-switch system consists of a prism rotating at 20,000 rpm. The pulse duration is 75 nsec with a rise time of approximately 20 nsec. As the pulse leaves the ruby crystal, a small portion of its energy escapes through the apex of the prism and impinges on a solar cell. The current pulse generated by the solar cell is used to start a 100-Mcps counter. Reflected energy from the target plus noise is detected by the photomultiplier after passing through the narrow optical filter centered at 6943A. When the photomultiplier signal becomes equal to a preselected decision level, the counter is stopped and the distance to the target determined from the counter indicator after division by 2. Obviously, the ranging accuracy is a function of the rise time of the laser pulse and the counting rate of the counter. A 20-nsec rise time would give an accuracy of ± 12 ft whereas the indecision of the counter gives a limiting accuracy of ± 6 ft.

This system is completely portable. The power for the unit is derived from cadmium-sulfide batteries. The pumping system uses an FX-38A xenon flashtube in an elliptical cavity. Cooling is provided by a small axial fan placed at one end of

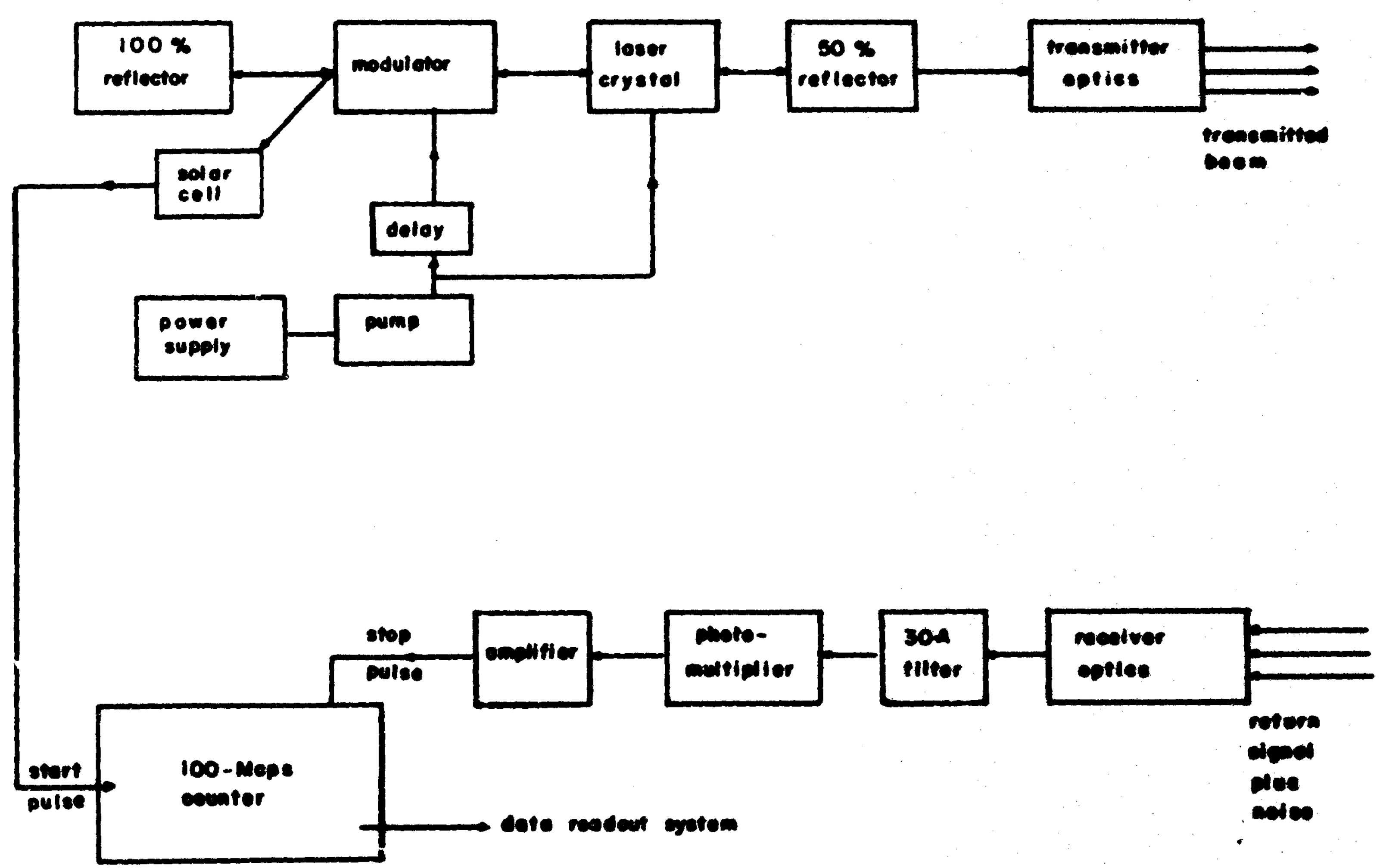

Figure 4.1. A Laser Ranging System

the cavity. The heat generated by the flashtube and absorbed in the ruby rod limits the firing rate to six times per minute. The unit is quite sensitive to shock and/or vibration since this can disturb the optical alignment of the prism and the ruby rod. Under favorable atmospheric conditions, this ranging system is capable of measuring range up to 12 miles.

4.3 Gas-Laser Missile-Tracking System

A more elaborate laser system has been designed by the Perkin-Elmer Corporation to provide precise trajectory data for various missiles during the early launch phases.[3] It is scheduled to be installed at Cape Kennedy, Fla. The system (called OPDAR for Optical Direction and Ranging) is intended to provide range, azimuth, and elevation data over any part of the trajectory from launch to 50,000 ft. From this data the position, velocity, and acceleration of the missile will be derived in a cartesian coordinate system. The allowed tolerance for error in the derived data is extremely small. For example, acceleration must be measured to 0.01 fps/sec and the position must be known to within 0.05 ft in the altitude range of zero to 500 ft. Normal pulsed microwave radars are not capable of this resolution and neither are pulsed laser systems. If a ranging unit such as described in Sec. 4.2 were to be tried in an attempt to obtain this accuracy, the time of the return pulse would have to be known to within 0.05 nsec, and there are as yet no means for defining pulse shape and measuring some identifiable portion of it with this precision. Also, pulsed lasers are not yet capable of operating at the high repetition rate necessary for the range and angle measurements.

The prime element in OPDAR is a CW laser (He-Ne; 6328A). It was double-modulated to provide the ranging data, that is, a 1-Mcps modulation signal provided range ambiguity resolution within 500 ft (the system was placed 10,000 ft from the launching pad) and a 100-Mcps signal provided ranging data to within 0.005 ft. Phase-sensitive detection was used in the receiver system.

It was necessary to use light as the carrier to permit the use of small-aperture radiators and reflectors. The radiating aperture was 2 in. in diameter; for a wavelength of 6328A this corresponds to a beam divergence of slightly greater than 2 sec of arc. A radar operating at a millimeter wavelength would require an aperture of about 320 ft to match this performance. Because of the difficulty in finding an object with such a narrow beam, a coarse tracking system was also used. The target on the missile is a trihedral or "corner cube" reflector 2.5 in. in diameter.

4.4 An Optical Heterodyne Detection System

A large step in the development of an optical communication system using coherent detection has been taken by the Sylvania Corp.[4] under an Air Force contract. One microwave-modulated gas laser was used as a source, and a second one as a local

oscillator (LO). An all-electronic feedback circuit was used to shift the LO frequency, enabling it to track the drift of the source laser. The LO frequency was simultaneously shifted 3.0 Gcps by single-sideband suppressed carrier modulation.[5] The two beams were then mixed and demodulated with a microwave traveling-wave phototube. The relative drift rate of one laser with respect to the other was only 3 Mcps/min under laboratory operating conditions. Although this will become much higher under field operating conditions, the electronic feedback system that enables the LO to track the source should have sufficient speed of response to follow it.

4.5 Problems in Using Coherent Light for Communications

The examples cited in Secs. 4.2 and 4.3 are applications of the laser where its properties of good directionality of the beam and high intensity are being used. The ultimate application of the laser in the communications field will use the coherence properties of the radiation. Recent investigations by a number of groups have shown, however, that the coherence is severely affected by the atmosphere. It is difficult to see how this can be overcome, and these deleterious effects may mean that propagation channels for coherent light communications systems may be limited to outer space or evacuated pipes.

Other problems dealing with the laser have yet to be solved. One of the main ones is to generate high-power single-frequency radiation so that coherent detection can be used. A sensible approach to solution has been suggested by the Sperry-Rand Corp. They propose to use a 1.06-μ line in the He-Ne gas laser system as a source and then use the 1.06-μ Nd:$CaWO_4$ laser for power amplification. Since the gas laser operates continuously, the long coherence time necessary for a coherent-detection long-range tracking system can be obtained.

Optical components used in coherent detection systems must be of excellent quality (say, $\lambda/20$ or better) so that the spatial coherence of the wave is not degraded. Broadband tunable lasers for use as local oscillators must be developed to permit cancelation of doppler shifts due to moving targets. Some progress, in addition to that cited in Sec. 4.4, has already been achieved in this area.[6,7] Even if optical components in the transreceiver are perfect, turbulence of the atmosphere will limit beam sharpness to several seconds of arc.[8] In addition, a great deal of power can be lost over a long communication link through molecular scattering and scattering due to suspended particles. Quite obviously, communication between points on the earth's surface or between earth and space will be limited to clear days.

4.6 Power Transmission

One way of avoiding atmospheric disturbances on the earth is to use light pipes to transmit the beam. Recent measurements[9] have shown that most of the power

losses in a system of this type were due to the 1 percent loss at the mirrors used to reflect the beam. The pipe was not evacuated, the wavelength used was 6328A. The estimated loss due to the transmission medium (air) was considerably less than 0.5 percent per transit through the 330-ft pipe.

Say the loss due to the air in the pipe was 0.1 percent per 330 ft. Then for power transmission, this system would not be competitive with normal power distribution systems whose losses are considerably smaller than this. If this loss could be eliminated by evacuating the pipe, then the system would compare favorably with standard systems.[10] Assuming a light pipe diameter of 12 in. and a wavelength of 0.7μ, the diffraction losses in the system would be only 0.05 percent per 20-mile hop.

4.7 Space Communications

It is evident that a number of the difficulties in propagating coherent optical radiation can be overcome if the transmission medium is a vacuum as it exists in outer space where no absorption, scattering, or distortion, of the wavefront occurs. A very probable application of lasers will therefore be in communication or power transmission between satellites. Here is one area in which the normal advantage of only a slight divergence in a beam becomes a disadvantage, since it is difficult to precisely point a very narrow beam. For one satellite to search for another would be almost impossible unless it had very good information on where to scan. If the target was a lens 4 in. in diameter and located one mile away, the solid angle of the target (of a total of 4π steradians) would be only 2.5×10^{-10}. This would be extremely difficult to find, it would be even worse if the search device was also narrow-beam. To overcome this problem on the ground, the initial searching is done with microwave radars whose beam divergence is very large by comparison with that of the laser. This would not be an acceptable solution in space, though, since it would defeat the primary purpose of using a laser for communicating. A possible solution to the problem would be to fit the transmitting satellite with an optical system that could on command produce an adjustable beam divergence with a feedback loop that would permit homing in on the target.

From most other viewpoints, the laser would be an excellent device for point-to-point communication in space. The beam can be so directional between two points that no outsider can pick up the information being transmitted or jam the receiver. In addition, the antenna and associated equipment are very small in size and therefore low in weight. This gives lasers a strong advantage over microwave systems since excess weight is extremely undesirable in satellite instrumentation. Injection lasers appear very useful in this area since they could be powered by solar cells and can easily be microwave-modulated.[11] NASA has shown interest in this area by awarding one contract for a 1500-mile slant-range voice communication system and another

study contract for a deep-space laser tracking system with a minimum range of 50 million miles. There is some doubt, however, as to the usefulness of the laser in this latter area.[10]

4.8 Land and Underwater Communications

In other communication areas, lasers are apparently not too useful. They will certainly never replace the normal megacycle-range carriers of radio and TV information, for the following reasons: (a) large-angle radiation patterns, rather than directional ones, are needed, (b) water vapor absorption is too great to overcome, and (c) the costs would be excessive, particularly when we consider the investment that citizens already have in standard radio and TV gear.

Since the first announcement of the laser, the Navy has been interested in obtaining one whose wavelength is in the blue-green region for underwater communication purposes. This might be acceptable for a short-range communication system, but it is estimated[12] that absorption and scattering would limit this distance to no more than 2 miles under the best transmission conditions. Consequently, this application does not look particularly hopeful.

4.9 A Rotation-Rate Sensor

In closing this necessarily brief discussion on the application of lasers to communications, it seems appropriate to describe one of the best laser applications to date since it is an excellent example of utilization of the coherence property of laser radiation. Using a ring type of traveling-wave gas laser, workers[13] at Sperry Gyroscope Company have demonstrated rotation-rate sensing with respect to an inertial frame of reference. Since a point on the surface of the earth is continually changing its direction owing to the spinning of the earth, the earth's movement around the sun, and the possible rotations of our galaxy through space, it is not an inertial frame of reference; and consequently, the ring laser can detect this rotation. A diagram of this system is shown in Figure 4.2.

First consider that the ring is not rotating. The resonant wavelengths λ_i of the ring laser are given by

$$k_i \cdot \lambda_i = L ,$$

where k_i is an integer (on the order of a million) and L is the total length around the loop. Since waves can propagate in both directions around the ring, angular rotation in one direction will make one path effectively shorter than the path in the opposite direction. This will cause the resonant wavelengths to be different for the two directions, and their difference will depend on the rotation rate of the ring. The beat frequency, as detected by the method shown in Figure 4.2, can be written as

$$\Delta f = \frac{4\omega A}{\lambda L} ,$$

where A is the area of the ring and λ is the wavelength of the light being used.

The rotation of the earth has been detected before in experiments with incoherent light, but a laser makes it much easier to do. The real application of this system will not be as a monitor of the earth's rotation rate, but as a gyroscope.

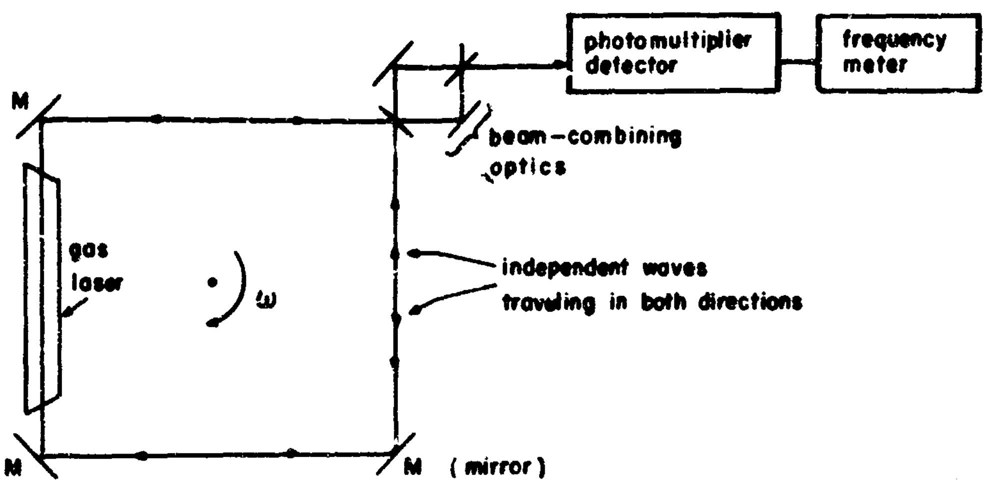

Figure 4.2. Laser Rotation-Rate Sensor

The present sensitivity of the ring rotation-rate sensor is 5°/hr, which is about one third of the earth's rate. Sperry predicts that it will be a straightforward matter to increase the sensitivity to 0.001°/hr which will put it in direct competition with the largest and most sensitive mechanical gyroscopes made today. These gyroscopes cost about $50,000; a laser rotation-rate sensor of similar sensitivity costs perhaps one-tenth the amount. Consequently, this device should generate a new class of navigation devices.

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5. APPLICATIONS IN BIOLOGY

The study of biological effects resulting from exposure to coherent radiation is one of the newest fields in medical research. Although only a few initial experiments have been performed, their results indicate that the application of lasers in this area will be rewarding. Very little is at this time known about the response of a living cell to coherent radiation, but several well-known medical laboratories are now studying this. A new Medical Laser Laboratory is now being established at the University of Cincinnati specifically for research in this area.

5.1 Areas of Study

Fine, Klein, and Scott[1] have written an excellent review article on the subject "Laser Irradiation of Biological Systems," which summarizes laser-related biological investigations that have been and are being made. The interested reader should consult this article, especially for its extensive list of references.

The studies[1] in this broad area can be grouped as follows: (1) the interaction of laser radiation with biological systems, (2) application of lasers as aids in understanding biological systems, (3) adaptation of laser devices for medical diagnosis and therapy, (4) assessment of the hazards involved at the power density levels attainable by lasers, on both a short- and long-term basis, and development of safeguards, (5) correlation of effects on biological systems with those on physical systems in order to assist in an understanding of underlying factors.

More specifically, it has been shown[2] that free radicals can be generated in animal tissue as a result of laser irradiation. Further studies are required to determine the nature of these free radicals and whether they differ significantly from those produced by heating. Studies on the blood group substances indicate that laser irradiation may enhance rather than decrease the biological reactivity of a molecule. Enzymes, proteins, single cells from many sources, microorganisms, plant cells, and intact animals have also been studied. Some specific studies and/or applications are summarized in the remainder of this section.

5.2 Malignant Tumors

Work that was reported on at the Second Boston Laser Conference (Northeastern University, August 1963) and the winter meeting of the American College of Surgeons

by McGuff, Bushnell, and Deterling indicates that laser energy has a selective effect on certain experimental malignant tumors of human origin that have been transplanted and have thrived in hamsters. Their experiments showed that the laser radiation produced regression or disappearance of the tumor; effects on normal tissue was minimal and healing was rapid. It must be emphasized that not all investigators have observed such effects and thus there is some uncertainty in the conclusions that can be drawn from these experiments. McGuff et al. have also investigated the effects of a high-energy laser on one human male that had recurring (after surgery) skin cancer. The one tumor of three that was fully irradiated disappeared almost entirely; a second one that received half as many shots from the laser receded by about 45 to 50 percent. The third tumor, which was not irradiated at all, lost about 20 percent of its malignant cells. Obviously, the results of this experiment are very encouraging, but much more work must be done before the ultimate usefulness of laser radiation in this area of medicine is known. Nevertheless, this example illustrates the potential application the laser has for medical research.

5.3 Cell Irradiation and Cauterization

Irradiation of single cells[3] by 3-μ-diameter laser beams has resulted in the destruction of several chromosomes; this indicates the possibility of studying genetics by selective destruction. The laser has also been used as a cauterizing tool on human beings, and for other local treatment of skin growths and blemishes. It was reported[3] that experiments to date indicate the laser to be superior to conventional cauteries in that it produces faster, clearer cures without secondary infections. Among other possibilities that have not yet been investigated are sterilization and microsurgery.

5.4 Retinal Surgery

The initial research efforts in this field have been confined to the effects of laser radiation on the eye. Soon after the first ruby laser was made it was shown[4] that lesions could be produced on the retina of the eye of a rabbit with energies on the order of 0.1 joule in 10^{-6} sec. This certainly illustrates the inherent danger in working with high-energy lasers.

The most immediate application that lasers will have in the biological area will deal with reattachment of the retina, the light-sensitive membrane on the rear interior surface of the eyeball. Images focused through the lens of the eye strike the retinal area and are transmitted to the brain via the optic nerve. If the retina becomes loosened, the individual gradually loses vision in that eye. High-power xenon arc lamps, which generate a moderately strong white light, have for a number of years been used in attempts to concentrate sufficient heat in the area of the unattached retina to cause it to coagulate and become reattached to its supporting tissue.

The difficulty with this technique is that the optical power that can be developed is limited. Consequently, to develop sufficient heat to reattach the retina, exposure times of several seconds are required. Also, since the light is heterochromatic it can not be focused sharply or positioned accurately. The ruby laser is practically a perfect solution since it can develop a short, intense, monochromatic pulse that can be positioned more accurately than the white light pulse. This is desirable to prevent eye damage by misdirected exposure. At least three firms have recognized the utility of the laser in this area, and are now manufacturing and testing laser retina coagulators.

In summary, the laser should have an excellent future in the area of biological applications and medical research. This prediction is strengthened by the development of pulsed gas lasers that operate in the blue and ultraviolet, where molecules and chemical reactions are considerably more sensitive than in the red. The laser's future will be particularly bright if further work substantiates initial findings that malignant tumors such as melanomas actually regress after irradiation with a high-energy laser.

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6. OTHER SCIENTIFIC APPLICATIONS

6.1 General Remarks

Many scientists feel that the laser will find its greatest use in the general sciences. This is certainly so at the present time and whether it stays this way remains to be seen. The number of uses for lasers in different areas of scientific experimentation is growing rapidly; high power and ultraviolet lasers are new developments, and because of the long delay in publication of results, there may perhaps be more applications that have not been published than have been. Certainly most sales by laser manufacturers have so far been to organizations that want to keep up with the laser field, or are doing research in lasers or associated areas. The number of people doing "research in associated areas" probably exceeds the number engaged in direct laser studies. Electrical engineers are rapidly moving into the field of optics and creating optical analogs of normal electronic circuits. Examples are devices such as optical modulators, demodulators, optical and infrared detectors, ratio detectors, power

limiters, optical filters, optical transistors, phased arrays, and parametric amplifiers. Very few of these devices require a coherent source on which to operate, and could consequently have been developed before the laser.

The laser has sparked a renaissance in the field of optics. It is the first significant device in this field during the past fifty years or more (some of the best books on optics were written as long ago as the turn of the century). The laser has in fact created a whole new field: nonlinear optics. The nonlinearity of optical materials has been realized for many years, but optical radiation that was sufficiently monochromatic and intense enough to observe such effects was simply not available. By using the appropriate type of crystalline material, scientists have succeeded in frequency-doubling with an efficiency as high as 20 percent. For example, by directing red light into one end of a crystal, they have been able to get red light and blue light with a wavelength of half that of the red light to emanate from the other end.

It seems hardly necessary to point out the impact that lasers have had on the study of materials for only through studies of this type are new laser frequencies created. A number of new types of crystalline materials have been developed for use as host materials for the rare earth or lanthanide elements, and it is quite reasonable to expect that these new materials will find uses other than for lasers. Our knowledge of the transition probabilities, lifetimes of metastable levels, and general spectroscopic structure of the rare gases and rare earths has certainly improved since these have become primary sources for the active laser element. For instance, many laser frequencies observed when rare gases were used were not predictable from previous knowledge. The study of various gas mixtures in a laser cavity designed to operate in the wavelength region from 20μ to 30μ has shown that in an electrical discharge a population inversion is more common than not. This conclusion is drawn from the fact that it is relatively easy to make a long-wavelength laser using almost any gas once the cavity (tube and mirrors) is properly designed.

Describing the subjects discussed above as "applications of lasers" is somewhat tenuous perhaps, but the examples do illustrate the tremendous impact the laser has had on many branches of science. The remainder of this section will be devoted to the discussion of well-defined application of lasers in the scientific area.

6.2 Raman Spectroscopy

The atoms of a molecule are never at rest but constantly vibrating about their equilibrium positions. To a good approximation a diatomic molecule behaves like a pair of weights connected to a spring, which follows Hooke's law. This vibrating system is defined by the usual expression relating the vibrational frequency f, the force constant K, and the masses for a harmonic oscillator, namely,

$$f = \frac{1}{c}\sqrt{\frac{K}{4\pi^2\mu}} \quad .$$

where the frequency is expressed in wave numbers, c is the velocity of light, and μ is the reduced mass of the molecular system. If f could be measured, the strength of the force constant between the two atoms in the molecule would be known.

Spectroscopy of the visible range is not difficult since sensitive detectors are available and there is relative freedom from noise. Most vibrational frequencies occur in the middle infrared, however, for which sensitive detectors are not available and where thermal noise presents many problems. The Raman effect thus becomes useful because it allows transitions to be observed in the visible region. Any material that will transmit visible light will scatter it quantum mechanically; this scattering virtually corresponds to the absorption and re-emission of the incident radiation. If the quantum state of the scattering atom or molecule is the same after the scattering process as before, the frequency of the scattered light will be the same as that of the incident light. If the scattering center is left in a different state, the scattered light will have been shifted in frequency according to the expression

$$f_1 = f \pm \Delta E/h ,$$

where f_1 is the scattered frequency, f is the incident frequency, and ΔE is the energy difference between the initial and final states. Whether the plus or minus sign is used depends on whether the scattering center is left in a lower or higher energy state, respectively.

In Raman scattering the intensity of the shifted radiation is always small compared with that of the incident radiation; also, when ΔE is small, f_1 lies close to f. Raman sources must therefore have high intensities and narrow spectral widths. These conditions are well satisfied by the ruby laser. A ruby laser having an output of 0.1 joule was used to observe the Raman effect and found to be about as good as a conventional red light source. Higher-power ruby lasers should therefore be very useful Raman sources since they may make it possible to observe lines that are too weak to be seen with conventional sources. The continuous-wave red He-Ne laser used as a Raman source[4] offers these advantages over ruby: (1) the Raman effect is proportional to the fourth power of the optical frequency used, (2) it is more convenient since it is continuous, (3) its spectral width is smaller , and (4) better Raman light-gathering geometry can be used. It should be useful for detailed Raman spectroscopy since its direction, polarization, and frequency are well defined.

It should be noted that stimulated Raman scattering has been observed.[5] Discovered accidentally in an experiment in which nitrobenzene was being used as the active material in a Kerr cell, this radiation was found to be coherent, to have excellent directionality, and in some cases to have an intensity that is 30 percent of the intensity of the incident beam. Thus, the Raman effect can be used as the basis of a technique for creating new laser frequencies.

6.3 Acoustic Waves in Solids and Liquids

The large optical electric field of the ruby laser can be used to induce coherent lattice vibrations in crystals. The process, known as stimulated Brillouin scattering,[6] is analogous to Raman laser action but with molecular vibration replaced by an acoustic wave of frequency near 3×10^{10} cps. The lattice vibration is amplified as it travels through the crystal with the incident light beam; a scattered light beam that is frequency-shifted is also emitted in accordance with the relations

$$\bar{K}_{\text{optical}} = \bar{K}_{\text{acoustic}} + \bar{K}_{\text{shifted}}$$

and

$$\omega_{\text{optical}} = \omega_{\text{acoustic}} + \omega_{\text{shifted}} \quad .$$

This process may also be viewed as either phonon maser action or parametric amplification. The intensity of the acoustic waves generated[6] has been approximately 1000 watts. Somewhat different effects have been observed in liquids.[7] Since intense optical fields are necessary to observe such effects, those of the laser will make it possible to study this process in a wide class of materials.

6.4 Ether and Relativity Experiments

One of Einstein's two basic postulates of special relativity was that the velocity of light was constant in an inertial frame of reference. This can be verified by means of the Michelson-Morley experiment. The surface of the earth may not be exactly an inertial frame but this experiment is not sufficiently sensitive to detect the difference.

Soon after the first laser was operated it was proposed[8] that lasers be used to look for an "ether drift" or anisotropy in the velocity of light since their short-term frequency stability can be on the order of one part in 10^{13}. A first experiment in this direction was performed[9] by using two gas lasers mounted at 90° to each other and rotating them to observe whether there was any perceptible change in the beat frequency. It was found that any frequency shift due to an "ether drift" is less than one part in 10^{11}, which may be regarded as confirmation to about one part in 10^{3} of the Lorentz-Fitzgerald contraction attributed to the earth's orbital velocity. This experiment is several times more accurate than any previous attempt to measure anisotropy in the speed of light, and will probably be repeated at various time intervals as the earth moves through space.

If ever developed to the point where it can be considered to be an independent time standard, the laser could be used to verify many ramifications of relativity theory. Launched into orbit for a period of years, such a precise time standard would allow exceedingly accurate measurements to be made of time, distance, and gravitational effects.[10]

6.5 Gas and Plasma Diagnostics

A plasma can be considered to be a high-temperature mixture of ionized elements having no net charge. Plasmas are of great interest today since they present possibilities for developing power (magnetohydrodynamic converters), play a role in space propulsion, and the ionosphere itself can be considered to be a weakly ionized plasma.

The study of plasmas involves, among other things, gathering data on their temperatures, electron densities, and electron velocity distributions. Placing physical probes into the plasma to measure some of these characteristics disturbs the plasma and masks proper interpretation of the data. Fiocco and Thompson[11] have recently observed Thomson scattering of ruby laser radiation (20-joule 800μsec pulse) from an electron beam, which illustrates the possibility of using lasers for plasma diagnostics. More recently, Schwarz[12] has observed scattering of a 0.1-joule 10^{-7}-sec pulse from a nonequilibrium plasma. Since the spectral distribution of light scattered by the free electrons in the plasma is related to the electron velocity distribution by the Doppler formula, the Thomson scattering method shows promise as a tool for plasma diagnostics. The use of fast high-intensity pulses is necessary since the plasmas change rapidly with time and have a high selfluminosity. The Air Force has let a contract to develop a precise plasma diagnostic probe.[13] The device shows promise as an inflight instrument for measuring the electron density distribution in the flow field of a reentering hypersonic vehicle and simultaneously measuring the electron temperature of the plasma at the same point. The ruby laser is also being used to study Rayleigh scattering from gases;[14] some deviations from Rayleigh scattering theory have been found as a result of this work.

6.6 Microscopic Spectroscopy

A new instrument on the market can be used for spectroscopy of microscopic-size samples without extensive sample preparation. Called the Laser Microprobe, it represents one of the first industrial or scientific applications of the laser. It incorporates a Q-switched ruby laser (1.0-joule 10^{-6}-sec pulse) whose beam is focused exactly onto the desired area of the sample being studied. Firing the laser creates a plume that contains partially ionized elements and chunks of the sample. Since it is a conducting plasma, its conductivity is utilized to cause a spark gap discharge through it, which ionizes it more completely. A standard optical system is then used to collect some of the radiation from the excited ions and focus it onto the slit of a standard spectrograph. Thus, in one flash of the laser the spectrum of the sample is recorded. There are a number of advantages in using a laser this way. First, the sample does not have to be electrically conducting and so a nonmetal inclusion in a metal matrix can easily be analyzed in situ; when a laser is not used it is necessary to excise the nonmetal sample and analyze it in a cap electrode or use some other method to make it conducting in order to have a route for the charge to leak off, as from the standard

spark-gap exciter. Second, a precise preselected area of the sample can be analyzed, whereas the spark-gap exciter produces a broad burn that cannot be constricted. The laser also eliminates the necessity for having direct contact with the sample. The spot size produced by the laser in this instrument is typically 50μ to 80μ in diameter; with a better optical system this spot size could be controllable down to, say, 5μ or up to as large a size as desired. Although this device is discussed under the heading Scientific Application it will certainly find many uses in industrial areas where quick and complete spectrographic investigation is necessary.

6.7 Defense Applications

If the number of articles published in popular magazines about the death-ray aspect of lasers indicates anything, it indicates that man is ever ready to believe that all things are possible. The United States Government is certainly taking a long look at this possible application, if we can judge from what we see in Aviation Week,[15] but it takes a true believer to accept that it will eventually be possible to direct and focus sufficient energy from the ground onto a target in the upper atmosphere in such a manner as to destroy it or even alter its course. It is interesting to note that energy amounting to 1000 joules is not sufficient to boil 1 gm of water. Admittedly, it will punch a small hole in a piece of steel that is in the focal plane of the lens, but this is a far cry from the true death ray or heat beam. Even if it were possible to harness a good fraction of Niagara Falls to fill a capacitor bank in order to store up 10^{10} joules to fire 10,000 separate lasers it doesn't seem likely that the device could fire very often, and any sort of optical system used in an attempt to focus such a beam would certainly have to be replaced after every shot. Much more likely applications will be for short-ranging units, detection of metal objects in fog or at night, and vision impairment of enemy ground personnel.

6.8 Measurement of Optical Properties of Materials

Gas lasers, because of their excellent coherence, narrow frequency, and directionality, allow many optical measurements to be made easier and more conveniently than normal light sources. They are typically used for measuring the optical quality of laser rods[16] and other large samples of optically transparent material, aberrations of lenses,[17] and indexes of refraction[18] to within ±.003. They also find use in schlieren photography—an optical technique for detecting density gradients in materials. The gradients (whether they occur in solids, liquids, or gases) produce refractive index variations that in turn show up as optical image distortions. An example of the use of this technique is in flow analysis over surfaces in wind tunnels.

6.9 Miscellaneous Scientific Areas

6.9.1 INSTRUCTIONAL AIDS

A portable gas laser that operates in the visible spectrum and has replaceable and adjustable mirrors can be an excellent tool for use in teaching students the properties of resonators, coherence theory, diffraction, interference, and the general properties of electromagnetic radiation. Judging from the number of high school and college physics laboratories in this country and abroad, there ought to be a good market for a low-cost laser of this type.

6.9.2 STELLAR INTERFEROMETRY

Our knowledge of the universe has come almost entirely from observations of visible light and radiowaves from the stars. Infrared astronomy could supplement optical and radiofrequency astronomy and perhaps even prove useful in its own right. A system has been proposed[19] for doing this by using the high-gain (50 db/m) 3.39-μ line of the He-Ne system since it is close to a window in the infrared absorption spectrum of the atmosphere.

6.9.3 GENERATION OF POWER IN THE FAR INFRARED

At the present time, there are no power sources beyond 133μ (.133 mm) or above—say—1000μ (1 mm). Tube development has practically ceased at 0.6 mm and it seems likely that lasers will close the gap. Laser sources have got to .133 mm (Sec. 2, Ref. 6) but output powers are very low (less than 10^{-8} watt). It has been proposed[20] that mixing two lasers would generate a difference frequency in the far infrared; this will certainly not be a very efficient system but it may produce more than masers would if they could operate at these wavelengths.

6.9.4 METEOROLOGY AND GEOPHYSICS

High-power lasers show promise of being useful research tools in meteorologic studies. Reflections of the laser radiation have been detected from stratified layers at altitudes of 80 and 120 km;[21] it is presumed that this occurrence results from meteor dust caused by the breakup of meteors at even higher altitudes. Other applications include: (1) measurement of clear air turbulence that is invisible to the eye or microwave radar (such instruments could be installed directly on the aircraft), (2) study of fog particles, (3) study of ice particles in clouds as a means of determining air temperature, and (4) measurement of land mass locations (geodesy).

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7. APPLICATIONS IN METALWORKING

7.1 Properties of Focused Radiation

Since it is in the metalworking area that the intensity of laser beams is used, it would be well at this point to review the limiting factors on focusing the radiation and the intensities that can be obtained.

It is well known from the theory of optics that the focused intensity I as a function of the radius r of a plane, spatially coherent, monochromatic wave is given by

$$I(r) = I_o \left[\frac{2J_1(\pi dr/\lambda f)}{\pi dr/\lambda f} \right]^2 .$$

where λ is the wavelength, f and d are the focal length and diameter of the lens used, $J_1(r)$ is the first-order Bessel function, and I_o is the intensity at the center (r = 0) of the focused spot. From radiowave transmission theory, I_o can be shown to be

$$I_o = \frac{\pi}{4} \frac{d^2}{\lambda^2 f^2} P .$$

where P is the power of the laser beam. The radius r of the focused spot is obtained by setting the argument of J_1 equal to its first zero, which is 3.83, that is,

$$\frac{\pi d r'}{\lambda f} = 3.83 ,$$

or,

$$r' = \lambda \left(1.22 \frac{f}{d}\right) .$$

It can be seen from this last equation that if f/d (the f/number of a lens) is made equal to 1/2, then the diameter of the focused spot will be approximately one wavelength.

It must be emphasized that this theory is valid for a uniform plane wave whose extent is greater than that of the lens (for example, in the case of light from a star). Generally this theory is not valid for a ruby or glass laser rod with the simplest focusing optics since the wave is not at all plane. In these actual cases the beam divergence is typically 1 to 30 milliradians. This is caused by the excitation of higher-order transverse modes (sometimes referred to as 'off-axis' modes) of the laser resonator; the order of the mode excited is a function of the ratio of the laser rod diameter to the cavity length. If a microscope objective is used to focus the radiation (assume a 1-cm focal length) the spot size would be on the order of 10μ to 300μ. It is still possible to obtain spot sizes from ruby lasers that approach a wavelength in diameter by using a suitably small aperture in the focusing system. In these cases the above theory is valid but considerable energy is wasted.

With $P = 500 \times 10^6$ watts, the focal length = 1 cm, and the beam divergence = 1 milliradian, the power density will be 0.6×10^{15} w/cm^2. This is a power density that is many orders of magnitude beyond anything obtainable using any other source of radiation. Since this can be concentrated in such a small spot, it is obvious why the laser has application in the metalworking area, for this is more than sufficient power to punch a hole in 1/8-in. steel. The hole-burning ability of a high-power laser is usually demonstrated by the number of razor blades it will burn through simultaneously. The unit for this measurement is the "gillette"; 10 "gillettes" represent a high-power system.

7.2 Theoretical Aspects of Laser-Machining; Hole-Drilling

Many speakers and writers have mentioned the application of lasers to machining and hole-punching, saying only that it would be useful and not providing an analysis of the problem. This is certainly reasonable because of the newness of the field and also because of the difficulty in analyzing the reaction that occurs when an ultrahigh energy beam impinges on a metal. Rothstein,[1] however, has made a semiquantitative analysis of the problem which qualifies him, better than most people, to make predictions about the usefulness of lasers in this field. The following is a very brief review of part of his theory on the reaction that occurs.

The source of radiation considered by Rothstein is the standard (not Q-switched) high-power ruby laser that generates many 10^{-6}-sec spikes, each of which contains about 10^{-2} joule of energy (10^{+4} watts peak power). Assume the volume involved is a cube 10 microns on a side, containing about 10^{13} atoms. If the heat energy required to vaporize an atom is 10 electron volts, and the 10^{-2} joule is equally distributed in the volume (1 joule = 10^{19} ev) each atom will absorb 10^4 ev; this will be more than enough to cause the small volume to vaporize. If each particle has only 1 ev more energy than is required to vaporize it, the effective temperature of the mixture will be 12,000°K (at 300°K, kT = .025 ev). The kinetic theory of gases gives as the pressure: $p = nkT$, where n is the particle density. From this we can deduce that p will be about 4000 atmospheres which explains why we see the vaporized material ejected in the form of a plume. Once again, if we use the kinetic theory of gases and assume $T = 10^4$ °K we can compute the average velocity of this plume to be 1 mm/μsec. Thus, if the next spike from the laser arrives within 1μsec, the thermally ionized atoms should have moved out of the vicinity of the hole, thus permitting the next spike to continue the "boring" process. Another viewpoint is to consider the plume as a plasma. Rothstein shows that the density of this plasma 1μsec later ought to be low enough for the laser wavefront to propagate through it unabsorbed.

An important conclusion can be drawn from this analysis: the radiation in the next spike can propagate through the plasma and bore a deeper hole. There are thus no strong limitations on drilling depth with a laser as there are for an electron or ion beam [which are: (a) the charged particles are badly scattered by the dense vaporized material, and (b) the evaporated material constitutes a plasma jet quite capable of turning into an arc discharge under the high-voltage conditions necessary to do machining with a charged-particle beam. This arcing can be severe enough to destroy both the sample and the apparatus]. Given the proper time-dependence of the spikes, it would be expected that the limitations on drilling depth would be set by the optical problem of maintaining a narrow beam over the desired depth, or by interference caused by redeposition of evaporated material on the walls of the hole.

The width of the hole should be controllable by defocusing the optical system used to focus the beam. The penetration depth should certainly drop at the same time if a constant-energy source is used. Rothstein has pointed out that it may be possible to machine holes that are smaller in diameter than the wavelength of light since peripheral cooling of the focused spot should restrict high evaporation rates to the central region.

It is unlikely that the laser will be used for the removal of large areas of metal. Instead, machining applications will more likely be confined to precision-drilling or perforating jobs. Material hardness does not present a problem since diamond and sapphire have been drilled. Another advantage in laser metalworking is that the 'cutting tool' can be removed from the workpiece. If need be, the workpiece can be in a glass-enclosed vacuum.

An example of what a laser might be capable of doing is given by the specifications on a USAF contract for precision-boring. The laser will measure and control six bore characteristics: diameter, roundness, taper, camber, bell-mouth, and surface finish. The accuracy (in diameter) is to be 8×10^{-6} in. for bore diameters from 0.05 in. to 0.09 in. and 5×10^{-6} in. for diameters from 0.09 in. to 0.25 in.

7.3 Soldering and Welding

The boring process consists in removing material, which a laser is quite capable of doing. On the other hand, soldering and welding are degraded by the loss of material; instead of removing material in the soldering, brazing, or welding processes, material is added to bond the original material together by heat. To prevent the plume from forming, the power of the laser beam has to be kept low since the internal pressure in the molten material is related to the temperature of the melt ($p = nkT$). What is required then is a laser source having high average power rather than high peak power. To build a continuous welder, it is estimated[2] that a 36-watt ruby laser could be used if operated at a rate of 100 pulses/sec, with each pulse lasting .001 sec. That the state of the art is not far from this is indicated by a paper[3] entitled "A High Repetition Rate Laser System." An average power of 30 watts at a prf of 60 pps was obtained with a 1/4-in.× 3-in. neodymium laser. The argon light source used was operated at $300^{\circ}K$ and air-cooled. The peak power was 1Mw, however, which would probably blast away the material to be welded but it should be a simple matter to increase the pulse length and thereby reduce the peak power.

Although continuous welders may be some time away, spot welders are being sold now by several companies. Specifications for one of them are: material, ruby; cost, \$6,000 to \$8,000; beam energy, 0.1j to 2.0j (adjustable); repetition rate, 12 ppm at 1j or 9 ppm at 2j; pulse duration, 0.5 msec to 1.5 msec; spot size, adjustable from 5 mil to 20 mil. An optical schematic drawing of a laser welder is shown in Figure 7.1.

An immediate use for these instruments will be in the microelectronics area where it is necessary (a) to join wires as small as 12μ [0.0005 in.] in diameter, (b) to weld thin films together, and (c) to connect small wires to films. These capabilities have already been demonstrated.

Energy requirements for spot-welding sheet stock up to 1/8-in. thick are not so great that welders for this use cannot be built now. Since 1500-j pulses are now possible, a limiting factor in making good welds may be the pulse shape and duration. Little quantitative work has been done in this area and little at the present time is known about the strength of laser-made welds. Investigations are in progress.

7.4 Other Metalworking Applications

Other application areas are the following:

1. Precision metal removal. The laser has been used to trim metal film

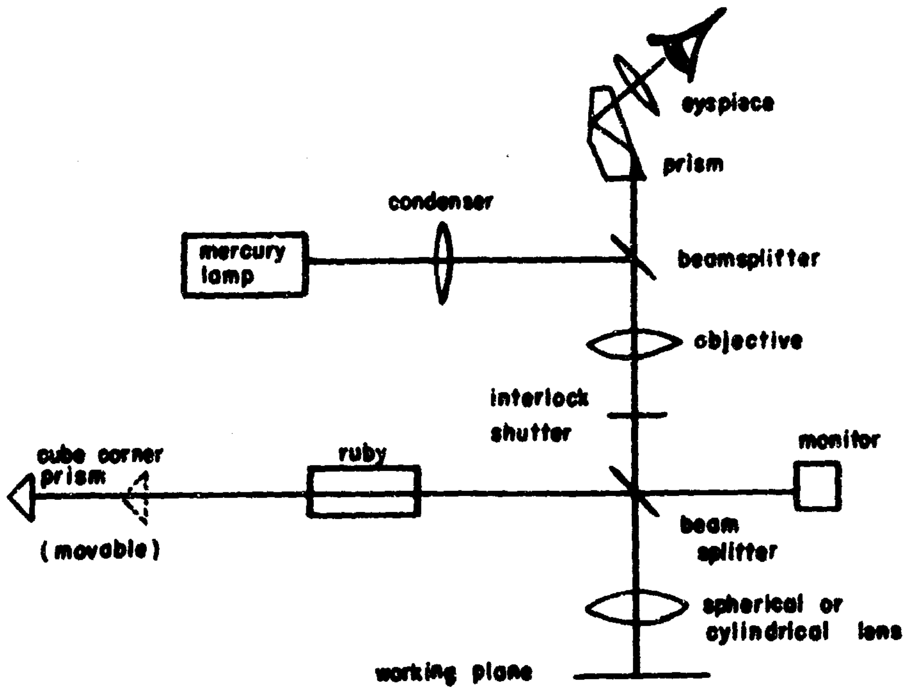

Figure 7.1. Optical System for a Laser Welder
(Courtesy of Electronics, July 5, 1963)

resistors[4] to within a tolerance of 0.1 percent and to remove microgram quantities of material from balance wheels, and gyro rotors while in motion.

2. Tunnel-diode alloys.[5]

3. Electric propulsion. What is the feasibility of propelling space vehicles with ions that are generated when a laser beam impinges on a piece of tungsten?

4. Generation of large pulse currents.[6] By focusing the laser beam onto a tungsten cathode current, densities of 20,000 amp/cm^2 can be produced.

5. Hermetic seals. The use of overlapping laser weld areas in geometric configurations can form hermetic seals that were exceedingly difficult to obtain prior to the advent of the laser.

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8. APPLICATIONS IN MISCELLANEOUS AREAS

Several applications have been suggested by a number of people but have not been developed appreciably at the present time. Since there is little information on these other than conjecture, they are grouped in the miscellaneous area. Also included are other applications that do not fit into the six previous categories.

8.1 Optoelectronics and Computers

The potential efficiency and inherent circuit compatibility of optoelectronic devices now being developed, such as diode lasers, light-emitting diodes, optical fibers, semiconductor photodetectors, and 'beam-of-light transistors' seem to indicate that optoelectronics is the next important area in the electronics field.

Diode lasers can be operated from transistor power supplies and easily controlled by a small current pulse since negative resistance effects have been observed in them.[1] Optical fibers show large net gains when used to transmit signals; used as lasers, these structures can generate optical logical operations.[2] Another attractive computer component would be a four-terminal device consisting of an emitter made from a laser and a photodiode collector. Since the only coupling between the emitter and collector is via the laser beam, it would be a four-terminal active device with excellent isolation between input and output. Circuit designers feel that such a device would have many advantages over the three-terminal transistor. It should be capable of operating at speeds approaching 1000 Mcps and have a current gain of close to unity.

There are a host of reasons favoring the use of optics in computers: (1) there is no charge buildup due to electrostatic potentials, (2) light transmitted in ordinary optical media is practically free from inductive and capacitive effects, (3) the high-carrier frequency means high-bit rates, (4) every lens system represents a system for parallel-processing of information, (5) circuit topological freedom allows easier coupling in three dimensions than with wires, (6) visual compatibility allows a more direct link with the operation, (7) high-density storage is possible because of the inherently high resolution obtainable with optical systems, and (8) read-in and read-out functions with presently used punched cards would be straightforward.

8.2 Display Devices

The diode laser makes possible a new family of display devices, suggesting a way of replacing, say, a conventional panel meter and indicating or warning light by a small, rugged, integrated device.[4] In the field of automatic control, graphic displays of system operating conditions and malfunctions are as essential as they are in aircraft and space vehicles. The high brightness, high efficiency and small size of the diode laser (assuming it can be made to operate without the necessity for cooling) can be used to advantage in these areas. Large-area diode displays could replace the

relatively bulky, fragile, low-brightness, low-efficiency, cathode-ray tube. The replacement could be a matrix of diode lasers, any single element of which could be selected by applying a voltage between the proper row and column. Scanned displays could be made by developing a proper sequence code to drive the diodes. Alphanumeric displays could be constructed by using suitable gating and control circuitry, and would be similar to the currently available electroluminescent displays but superior to them in terms of brightness, life, and speed.

Another approach to display systems is through electronic beam deflectors.[5] These make use of electrically induced birefringence in crystals; estimates are that as many as 10^6 deflections/sec are possible. Ten of these crystals in series could produce 2^{10} possible positions.

8.3 Phase Photography

Normal photography uses only the intensity of the light from an object to form an image. Thus, half of the available information—the phase—is not used. A photographic process[6] that uses this information has been perfected by scientists at the University of Michigan. It yields excellent image contrast and allows high magnification. In conventional microscopes, magnification is dependent on glass lenses and even the best of these produce some distortion. The new technique would avoid these distortions since no lenses are used, and would produce clearer, sharper images.

The technique consists of two steps. First, coherent light is transmitted through or reflected from an object, and recombines on a photographic plate with laser radiation that by-passed the object; the mathematical analysis[6] shows that what is recorded on the plate is the Fresnel diffraction pattern of the object. Second, after the photographic plate has been developed, it is illuminated with coherent light; the desired image then appears at a certain distance from the plate. (The writer does not expect the reader to understand the process from this intensely abbreviated description; the process is quite complicated and the interested reader should consult Ref. 6 and Ref. 7.) The greatest use for this system will probably be found in the laboratory where high-quality reproduction or magnification is desired. The ideas embodied in this technique could also be of use in producing clearer and sharper x-ray films since x-radiation is also coherent.

8.4 Chemical Applications

As a direct result of making lasers, much information has been obtained on the spectra of the inert gases and rare earths and on the transition rates between the different allowable electronic levels of these atoms, but no new publications have appeared on the "chemistry" of these elements or on the influence a laser might have on a chemical reaction. Since chemical reactions are intimately involved with the energy level structures of their atomic and molecular constituents, dissemination of the increased

knowledge of energy levels brought about by lasers could perhaps aid in understanding the processes involved in some reactions.

A much broader area of discovery would be the use of a laser as a selective catalyst in a chemical reaction. Nearly all chemical reactions are now triggered by thermal agitation of the atoms and molecules, which appears to be a rather crude technique. Heat will excite every atom in the mixture, but irradiation by a laser beam would excite only those atoms that had absorption bands at the laser frequency. Although such experiments sound academically interesting, it is not known at this time what their ultimate usefulness will be. It is somewhat surprising that no work has been reported in this area, but this may simply reflect the fact that it takes time for progress in one field to influence another. Certainly, a desirable tool in chemical research would be a tunable laser that would permit many interesting investigations such as of bond strengths and absorption characteristics. This development is unlikely since many lasers would probably have to be used at different, discrete frequencies. The largest range of tunability that the writer is aware of is 100A.

8.5 Light Sources

8.5.1 LIGHT BULBS

The possibility of using injection lasers for light bulbs is not nearly so far off since laser emission in the blue (4560A) has been detected from SiC.[8] On the validity of this claim there is a difference of opinion[9] among scientists. Be that as it may, the diode laser still has an excellent future as a light bulb. The efficiency of standard light bulbs is approximately 10 percent and, as we know, they burn out. A diode laser such as SiC should be able to operate without having to be cooled. It could be connected directly across an ac line and operated as a light source that does not wear out, with an efficiency of, say, 30 percent. The coherent monochromatic radiation that would be produced could be converted to heterochromatic light by surrounding the laser with the proper type of phosphor that would absorb the laser light at 4560A and then reradiate it over a band of frequencies determined by the type of phosphor used.[10] As mentioned above, SiC may not be the type of laser that will be used in this application, but its operating properties are typical of the type of semiconductor that will be used, and the example serves to indicate the possible simplicity of the application.

8.5.2 HIGH-SPEED PHOTOGRAPHY

The application of the ruby laser in high-speed photography has already been demonstrated. Using the normal spikes from the ruby laser as the source of short, high-intensity flashes, Yajima et al.[11] directed the laser beam onto the surface of a circular mirror and then fired a bullet in front of the mirror. The illumination was very even, and clear photographs of the bullet moving at 170 m/sec were obtained. Since Q-switched lasers can produce spikes as short as 7×10^{-9} sec, they could be

used to capture an object moving at 80 miles/sec (a factor of 10 faster than a satellite) with little blur.

8.5.3 MICROGRAPHY

The high intensity and directionality of the laser beam allow intense illumination of small areas or objects. Courtney-Pratt[12] took a microphotograph of a metallic surface under high magnification by means of a single flash from a ruby laser, and found the laser much faster than the most intense flashlamp available. He also demonstrated that the light from the ruby laser is useful for studying details of topography; when the surface to be studied is placed in approximate parallelism with a known or reference surface and illuminated with the laser beam, high-contrast stable fringes are produced. Until now the standard technique has been to use a mercury discharge lamp, which is sufficiently monochromatic but because of its low brightness requires long exposures producing fringes that tend to be fuzzy owing to vibration and heating effects. Where the laser was used, the exposure time was reduced by a factor of 20,000 and sharper fringes resulted.

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9. CONCLUSIONS

It is apparent that lasers have not yet lived up to the expectations people had for them when they were first developed but are still "a solution looking for a problem." Comparisons between the laser and the transistor in the area of applications are not justified since the transistor found immediate uses simply by replacing vacuum tubes.

Such a broad-based application does not exist for the laser, and it will consequently take considerably longer than was initially expected for a market to develop. Whether the dollar volume of lasers will ever approach that of transistors is not known. At the moment it appears that the greatest use for it will be as an instrument for scientific and medical research, and for performing many tasks in a much more effective manner than could be done with a conventional light source.

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